



South Asian Monsoon Extremes and Climate Change

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Abstract

South Asian monsoon (SAM) is an important segment of the tropical monsoon system that mainly lies in the range of the seasonal oscillations of the intertropical convergence zone (ITCZ). About 70% of total rainfall in South Asia occurs during monsoon months each year, between June and September. Even within season, rainfall pattern is highly variable. The South Asian developing countries are mainly agro-based economies and livelihood of rural population is mainly dependent on natural resources which revive through the monsoon. The South Asian monsoon has influence on global atmospheric circulation and its future behavioural patterns will have serious implications for the entire world. Monsoon seasonal rainfall has temporal and spatial variability. There is no significant trend in Monsoon rainfall over past 100 years over the entire South Asian region. Ocean–atmosphere coupling in terms of ENSO and IOD has significant correlation with performance of monsoon over Indian subcontinent. IOD and ENSO are playing complementary to each other and maintaining good monsoon during recent decades. Along with year-to-year variability there exists intra-seasonal variations which are more markedly noticeable nowadays. These are in the form of prolong dry days with no rain or little rain and prolong wet days with rather good to very heavy rain forming a cycle of active and break spells. Extremes occur during active and break spells of monsoon. The extreme rainfall events mainly occur during synoptic scale weather systems like lows and depressions. Extreme events like flood, drought and more landslides are high impacting events that need proper strategies to overcome the adversities. The present study focuses on monsoon extremes, intra-seasonal variations and modulation by remote

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forcing and their future trends in global warming scenario. The global ocean–atmosphere coupling and its linkage with South Asian monsoon is on chance and how it will be progressing in future.

Keywords

South Asian monsoon · Rainfall · Extreme event · Atmosphere · Natural hazards

4.1 Introduction

South Asian monsoon is basically summer monsoon on Indian subcontinent and is large-scale manifestation of ocean–atmosphere coupling (Hernandez et al. 2015; Ramaswamy 1965). The monsoon rainfall is mainly driving agricultural production supporting food security and steering economy of South Asia. The word monsoon is basically having its origin from Arabic language. Monsoon is a season during which reversal of wind direction takes place over a large geographic area. South Asia, Africa, Australia and Central America’s Pacific coast are the main monsoonal regions of the world and mainly characterized by wind reversal during winter to summer or summer to winter transition mainly (Buckley et al. 2014). These are extended on tropical region 25°S to 35°N, 30°W to 170°E. Indian monsoon region is main central region of the South Asia. Wind reversal during seasonal transition can be understood by global pressure and wind patterns in January and July. The Siberian High of northern Asia and polar highs are main features of the winter (January) circulation in northern hemisphere with two intense low-pressure centres (the Aleutian low and the Icelandic low) situated over the North Pacific and North Atlantic, respectively, while in the summer months, the sub-tropical high-pressure areas of Northern Hemisphere shift westward and have more intensity than winter months (Sonwani and Saxena 2021). These strong high-pressure areas regulate the summer circulation over the oceanic regions and supply warm moist air on to the continents that are situated to the west of these highs leading to precipitation over parts of eastern North America and Southeast Asia. The changes in pressure patterns reverse wind from north-easterly in winter to south-westerly in summer (Fig. 4.1).

Monsoon can also be considered as atmospheric response of variable sun radiation governed by seasonal movement of sun. The movement of sun between Tropic of Cancer in Northern Hemisphere and Tropic of Capricorn leads to differential heating on different land and oceanic masses and generates significant temperature gradient which is opposite in direction compared to winter season (Lau and Li 1984; Webster 1987; Meehl 1992). This temperature gradient is basically responsible for the generation of low-pressure areas and faster wind movement towards these low-pressure areas through wind convergence along with vertical lifting of air masses and formation of clouds.

Moreover, if we look at general circulation patterns of atmosphere, we find alternate low- and high-pressure belts in both hemispheres. The equator is low-pressure belt where low-level surface north-easterly winds converge over a

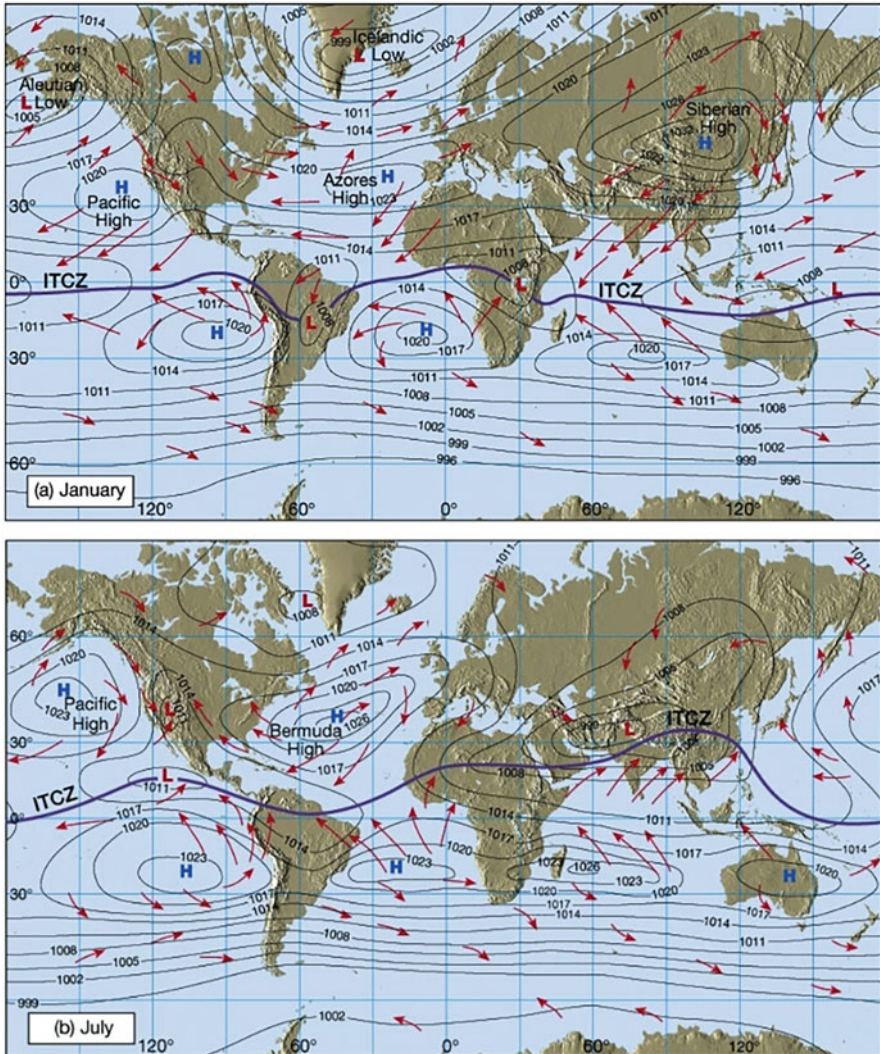


Fig. 4.1 Average surface pressure and associated global circulation (Source: The Atmosphere-An introduction to Meteorology, Book, Eleventh Edition, Authors: F. K. Lutgens, E.J. Tarbuck Illustrated by Dennis Tasa) source : The Atmosphere, 8th edition, Lutgens and Tarbuck, 8th edition, 2001

broad area forming inter-tropical convergence zone ITCZ. In monsoon season, it travels across lower latitudes of the Northern Hemisphere and in winter season shifts towards Southern Hemisphere low latitudes main (Gadgil 2018). The average position of ITCZ is a few degrees north of the equator due to extensive land masses of the Northern Hemisphere as compared to Southern Hemisphere creating

maximum heating zone in Northern Hemisphere and equatorial trough remains in this maximum heating zone. The position and movement of this convergence zone is linked with movement of sun and formation of new low-pressure areas further north of its position. Monsoon can also be defined as gradual movement of ITCZ towards north and south with movement of sun. The movement of ITCZ is a characteristic feature of South Asian monsoon (Turner and Annamalai 2012).

South Asian developing countries maintain increase in growth rate from past few years except covid 19 pandemic crises. These countries have large domestic market and agro-based economy well maintained by regular robust monsoon. The growth of agriculture sector, work-based requirement and demand in domestic market are directly linked with performance of monsoon. The monsoon rainfall and its intra-seasonal variations are deeply affecting life of 1.89 billion people. The well-noticed variations in dry and wet spells and high impact extreme events like floods, droughts, severe thunderstorms and landslides during monsoon season carry atmospheric response to anthropogenic activities which can be quantified through meteorological and other related observations needed to understand climate change and associated risk. The prediction of onset and withdrawal of monsoon and also dry and wet periods is of key importance. The good quality observational data sets can help future climate management strategies for land-based water resources, ground water, agricultural best practices, food security, disaster early warning and preparedness, and infrastructural needs. The synoptic meteorology seems very important in this regard. Assessment of large-scale semi-permanent features based on observed data and how the synoptic features have modulated under various ocean–atmosphere forcing in recent climate change scenario are also addressed in this chapter.

4.2 Semi-permanent Features of Monsoon

4.2.1 Heat Low

The low-pressure area develops over Pakistan and North West India, also called “heat low”, indicating thermal heating conducive for its formation. The Hindukush mountains regionally play important role in its formation. Its location and intensity are significant for monsoon advancement process. Intensity of heat low is correlated to rainfall activity (Ramage 1971). The negative pressure departure in heat low region and positive pressure departure in peninsula are favourable for monsoon progress. Heat low formation starts from May and get established by June near to its normal position. Some variations occur in spatial position and strength of heat low during monsoon season but mostly it remains at its normal position and gradual weakening starts from September and vanish in first fortnight of October. The observed minimum values of the heat low were 992 hpa to 994 hpa during June and July and 996 hpa to 1000 hpa in August and September for the year 2016.

4.2.2 Monsoon Trough

The seasonal trough line, starting from heat low over Pakistan and adjoining areas, extending in southeast direction and passing through West Bengal's Gangetic region and reaching up to eastern part of West Bengal and Orissa known as Head Bay. The low-pressure line generally runs from Ganganagar to eastern West Bengal coming through Allahabad, having westerly to south-westerly winds in the south of the low-pressure line and easterlies to the north of the low-pressure line. The position of the low-pressure line oscillates on day-to-day basis and affects the monsoon rains. When the trough is near to the foothills of Himalayas termed as "break in monsoon" as there is decrease in rainfall activity over most parts of the country, though the Himalayan mountain region get good and heavy falls leading to occasional overflow of rivers creating floods. The migration towards south direction of trough from its mean position, i.e. the central parts of the country, under the influence of monsoon depressions forms in the northern Bay of Bengal and generally moves in westerly and west north-westerly direction across Indian land mass, giving widespread rainfall with some heavy to very heavy rain spells over the central India and some parts of peninsula. The oscillations of monsoon trough about its mean position govern active and break phases of monsoon. The total number of days in these positions is crucial for seasonal rainfall. In September month, western end of monsoon trough shifts near to foothills of Himalayas and eastern end remains south of its normal position and during last 15 days it almost vanishes.

4.2.3 Tibetan Anticyclone

Elevated Tibetan plateau by regular sun heating starts transferring its heat to upper winds acting as a heat source and plays significant role in global circulation and South Asian monsoon or Indian monsoon. The heating of the plateau just reverses the meridional temperature gradient throughout the troposphere. This reversal is the main factor which brings changes in seasonal circulation over East Asia, with poleward shift of the subtropical jet. At 500 hPa it is situated to the east of Long 80° E with axis near about 28° N. It is more intense at 300 hPa and extends between 70° E and 110° E. The rainfall and its distribution are linked with east west well-oriented Tibetan anticyclone. The location of anticyclone changes during the monsoon and corresponding changes occurs in rainfall also. It has been observed that when it shifts towards west from its mean location rainfall activities get enhanced over western Himalayan region. Shifting of anticyclone towards west or southwest of its mean position enhances rainfall in northern India and shift towards north or northeast of mean position decreases rainfall over northern regions.

4.2.4 Tropical Easterly Jet (TEJ)

Strong concentrated easterly winds in the form of jet are seen in upper air wind charts located south of subtropical ridge over Asia. It is having centre over Chennai city latitude and prominent at upper tropospheric level, i.e. 100 hpa, mainly during the month of July. The Tropical Easterly Jet (TEJ) starts from eastern coastal areas of Vietnam and runs up African west coast. The jet gains strength over the region of South China Sea and southern Indian region, and after crossing this it starts weakening. A broad latitudinal spread of jet winds during monsoon months has been observed through wind charts and maximum wind velocity of 126 knots at upper tropospheric level around 154 hPa pressure level was recorded at Guwahati in radiosonde data. These easterlies of jet provide steering to LPSs formed in Bay of Bengal for westward movement. The jet is likely to weaken resulting in reduced wind shear favourable for more cyclonic storms (Brahmananda Rao et al. 2008).

4.2.5 Mascarene High (MH)

The strength of cross-equatorial flow is maintained by intensity and location of this high. It is a part of high-pressure belt located at subtropical latitudes in southern hemispheric Indian Ocean centred at 30° S/50° E, termed as Mascarene High. This high pressure generally forms close to the Madagascar island off the coast. The waves coming from extra tropics cause small duration fluctuations in its intensity (Sikka and Gray 1981). The increase in intensity of Mascarene High accelerates the moist wind current crossing equator at lower levels and forms a jet stream type of flow also known as low-level jet and identified as wind field associated with monsoon strength over regions of Arabian Sea. On similar lines decrease in intensity of this high weaken the cross-equatorial flow and monsoon current. The parameters like temperature over sea surface (SST), heat energy content of ocean and sea surface height (SSH) are on increasing trend over its region as evident from observations of recent 20 years. The warming of sea surface aids in curtailing the pressure at sea level resulting in feeble or weak gradient of pressure between the Mascarene high and the pressure over land and oceanic regions of Northern Hemisphere (Vidya et al. 2020).

4.2.6 Somali Low-Level Jet (LLJ)

Inter-hemispheric lower-level strong wind flow as a jet stream having location of core near 850 hpa appears flowing from Mauritius across Kenya, also called Find later jet or low-level jet. The lower-level strong winds with highest speed around 40–60 kts identified at core of the wind field over SE Arabian Sea and adjoining Peninsular India is a part of this Somalian or Find later jet. The frequent westerly waves of extra tropical origin modulates its intensity. Strong cross-equatorial low-level jet (LLJ) increases rainfall activity around entire west coast of India. The

wind speed at core, depth of westerlies, zonal water vapour flux, horizontal wind shear and cyclonic vorticity show an increase near to the heavy rainfall days and a decrease afterwards (Xavier et al. 2017). The fluctuations of LLJ or Somali jet can be assessed through Somali jet speed index (Boos and Emanuel 2009). The LLJ intensity changes within 20- to 90-day period, in relation with the northward-advancement of active and break phases of the monsoon (Swathi et al. 2020).

4.3 Phases of Monsoon

4.3.1 Onset of Monsoon

The monsoon over south Asian land reaches initially at Andaman and Nicobar Islands around 20 May normally and starts moving towards Indian land; strong wind flow from Southern Hemisphere to Northern Hemisphere mainly cross the equator as strong concentrated wind flow, termed as low-level jet (LLJ) or Somali jet or Find later jet, and establishment of tropical easterly jet at upper level (100 hpa) is the main feature of wind charts during the onset phase. Onset date of monsoon over Andaman and Nicobar Island is based on actual observations, model forecast and convection in satellite imageries. The Zonal winds of 8 mps at 925 hpa and westerly wind up to 600 hpa and Outgoing Longwave Radiation (OLR) equal to or less than 210 watt/m² with fairly widespread or widespread rain over islands are realized in actual observation. Monitoring all such parameters for few days the onset date over Andaman and Nicobar can be declared (Debnath et al. 2019). The India Meteorological Department every year announces onset of monsoon over Kerala state considering three parameters: precipitation, wind speed and wind velocity, and vertical depth forming, i.e. wind field and outgoing longwave radiation mainly. The temperature gradient in the upper atmosphere, i.e. 700 hpa and 500 hpa, get reversed during onset (Ananthakrishnan and Thiruvengadathan 1966). The kinetic energy at low level, total kinetic energy generation in vertical direction and total available tropospheric moisture over Arabian Sea may also be used as possible predictors for onset date over Kerala (Raju et al. 2005). Normal date of monsoon arrival over Kerala is considered to be 1 June with a deviation of 7–8 days prior or later. Sea surface temperature gradient (SST) over Indian and Pacific Ocean have linear correlation with onset date on decadal time scale (Preenu et al. 2017).

4.3.2 Monsoon Advance

The progress of monsoon varies from year to year. Monsoon advances by two branches, one is Arabian Sea branch and the other is Bay of Bengal (BOB) branch. The Arabian Sea branch soon after onset over Kerala moves northward along the west coast and covers Gujarat region near June 15. Whole Peninsula and Central India get monsoon rainfall through this branch. The BoB branch moves northward and enters regions of Bangladesh, Assam and adjacent north eastern states. The

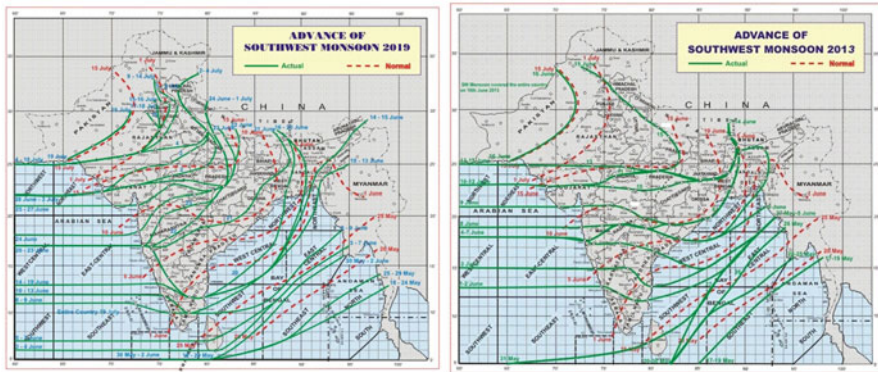


Fig. 4.2 (a) Monsoon onset and progress 2019; (b) Monsoon onset and progress 2013 (Fast Advancement) Source: India Meteorological Department; <https://www.imdpune.gov.in/Weather/weatherforecast.html>)

height and orientation of the hills of Assam, Meghalaya and Myanmar create obstruction, resulting in deflection of BoB branch in west direction under the Himalayas range. The BoB branch reaches over the Gangetic plains of north India in the form of south-easterly/easterly winds. The branches meet over north India around longitude 80° E. Monsoon takes 15–35 days to cover the entire country as observed during 2010–2020. Monsoon progressed fast in 2013 and taken only 16 days to cover the whole country.

Formation of low-pressure systems (LPS) in Indian Ocean region may facilitate timely onset of monsoon over Kerala or it may cause delay in monsoon advancement over Arabian Sea. In this context, the location of formation of system, its intensity and track are of much importance. The LPSs in BOB and Arabian Sea disturb the south-westerly wind flow coming from Southern Hemisphere crossing the equator. Sometimes the flow gets intensified favouring fast monsoon advancement over country and sometimes flow get decreased giving a temporary halt to the advancement of monsoon. The advancement of monsoon is not a continuous process during some periods northern limit of monsoon remain stagnant for 5–6 days or even up to 10–12 days and termed as hiatus in monsoon. The normal dates of monsoon progress (onset and withdrawal) have been revised by India Meteorological Department based on 1961–2019 data. The progress of the monsoon is sometimes fast and sometimes slow (Fig. 4.2).

4.3.3 Withdrawal of SW Monsoon

The withdrawal of monsoon starts from north western part of country in the month of September. During past decade 2010–2020, the withdrawal generally commenced from third week of September and took 15–30 days or even more for the entire country. The important meteorological aspects to be looked into for the withdrawal;

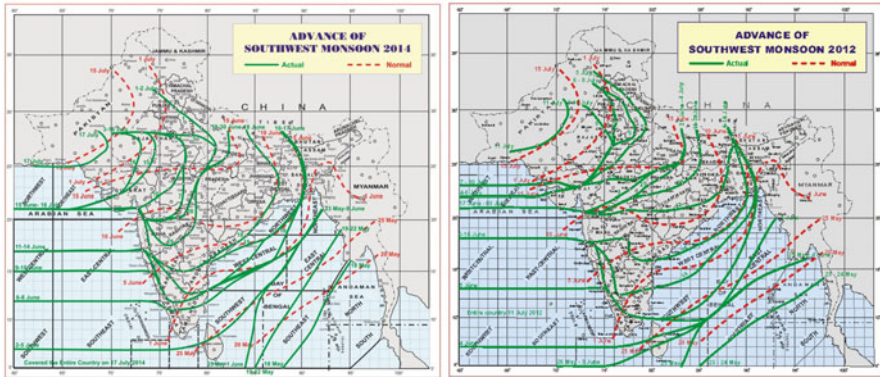


Fig. 4.3 (a) Monsoon withdrawal 2014; (b) Monsoon withdrawal (Fast) (Source: India Meteorological Department; <https://www.imdpune.gov.in/Weather/weatherforecast.html>)

no rainfall for consecutive 5 days and development of anti-cyclonic circulation which can be seen at 925 hPa or 850 hPa levels in upper air charts, i.e. reversal of vorticity field in the lower troposphere and dominance of northerly or north-westerly winds in over northwest India, shift of ITCZ in south and rapid reduction in available moisture in middle and upper atmosphere may be observed through satellite water vapour imageries and radio-sonde data. During past decade, most of the monsoon withdrawal commenced in late October month, so monsoon withdrawal dates has been revised based on operation dates data 1971–2019 (Fig. 4.3).

4.4 Intra-seasonal Variations/Active and Break Spells

Indian monsoonal system is a segment of large-scale circulation patterns associated with monsoon over Asian countries and having different temporal variability on daily, seasonal, annual and decadal time scale. In general term, active spells mean period of good rainfall days and weak/break spells are days of little rain or no rain. The long period of active spell or a greater number of days of good rainfall impacts monsoon rainfall of the country and with widespread spatial coverage fulfil agricultural needs and water requirements of the country. Similarly, long period or more days with no rain, i.e. breaks, impacts the total precipitation in monsoon (Gadgil and Joseph 2003) and adversely affect crop growth and management practices. The timing of occurrence of break spells is also very much crucial for agriculture and if coincides with period of crop maturity it will affect crop yield. Long and frequent break spells may lead to drought situation.

A break situation arises by shifting of low-pressure trough near to Himalayan foothills as defined by (Ramamurthy 1969). In this situation more rainfall in Himalayan region and rainfall activities get reduced in other parts of country. The position of monsoon trough is very critical for determining active and break spells.

When monsoon trough migrates towards south of its mean position good rainfall received over central and other coastal states of the country making monsoon active.

Earlier surface pressure and wind patterns were used for identification of breaks over the Indian region. A break could be identified by disappearance of easterly winds from sea level and 850 hPa charts at least for 2 days (Blanford 1886; Goswami and Mohan 2001) zonal winds at 850 hPa over the Bay of Bengal, used for “active” and “break” situation. The high frequency of active spells leads to strong monsoon and more number of break spells leads to weak monsoon. The variations with in the season ultimately decide the seasonal mean. The intra-seasonal variations are dominated by small time scale processes very chaotic in nature.

The positive OLR anomalies over western portion or segment of monsoon trough, i.e. northwest and central India is an indicative of break and the average OLR should exceed 10 Wm^{-2} , (Krishnan et al. 2000). Daily rainfall anomalies over Indian core region $73\text{--}82^\circ\text{E}$, $18\text{--}28^\circ\text{N}$ were also used to define the active and break (Mandke et al. 2007). Low-pressure systems form and move over Indian subcontinent during active phase of monsoon and these systems generally follow the monsoon trough and clustering of clouds takes place around that trough line (Goswami et al. 2003). The gridded data sets prepared and used for classifying active and break spells using standard rainfall anomaly over a region (Rajeevan et al. 2006, 2010).

Indian Summer monsoon rainfall (ISMR) have significant negative correlation with break days and significant positive correlation with active days but the relationship of ISMR with break days is stronger than those of active days. Active and breaks operate on 10–12 days’ time scale.

Revival of active spell after break spell is mainly governed by oscillations of monsoon trough. When a weather system of low-pressure develops in Bay of Bengal (BoB) under influence of cyclonic upper air winds, it pulls down the monsoon trough towards south. Monsoon trough again migrates to its mean position or further south of its normal position giving lot of rains in various states. The spatial coverage, intensity and period of rain depends on intensity of low-pressure system, its track and strength of moist winds and support from geographic features like mountain range or big water bodies. The LPS move Northward initially or North-westward along the monsoon trough (Goswami 1987; Sikka 1977). Some LPS formed in Bay of Bengal (BOB) entered Arabian Sea water after crossing Indian land while some LPS of BOB move Northward and then recurve to North-eastward towards Bangladesh and Myanmar. These systems following different tracks give wide-spread rain and make monsoon active again.

The second way of revival is through northward propagation of tropical convergence one. The deep convective clouds get oriented in east west direction in Indian subcontinent region linked with tropical convergence zone (TCZ) during active spell (Sikka and Gadgil 1980). The life period of active spell is small as compared to break spells, so after the dissipation of deep convective clouds associated with TCZ, there should be northward propagation of freshly formed convective clouds from the equatorial Indian Ocean, so TCZ has two arms—one on Indian land mass and the other on ocean. When land arm is active, the oceanic arm is in formative or beginning stage, and when land arm gets dissipated, the oceanic arm gets developed

with convective clouds and starts propagating towards northern latitudes with winds and starts rain leading to revival from a break phase.

4.5 Extremities in South Asian Monsoon

The rainfall extremes are high magnitude rain particularly above threshold value for a day or more number of days leading to large runoff on ground. South Asian nations receive rainfall via southwest monsoon. In Asian continent, monsoon extreme event frequency has been increased (Yao et al. 2008; Shrestha et al. 2017). The change and rise in of extreme also assisting probability of the event to an increase noticed over various regions of countries situated in South Asia (Christensen et al. 2007). Some opposite trends of decreasing precipitation over a time period of 30 years from 1976 to 2005 and large regional variations of high intensity rainfall events have been observed addressing impact of regional variability over Pakistan (Salma et al. 2012).

The monsoon season extreme rainfall events (rainfall >124.4 mm in a day) over Indian region have spatial variability over selected regions like entire west coast, some parts of central and northeast India. The significant rising trend of frequency of extreme rainfall over the Indian monsoon region season and significant increasing trend during June and July months during period 1951–2005. The increased fraction of extreme rainfall events to the total seasonal is compensated by a significant decreasing trend in rainfall (rainfall $R \leq 64.4$ mm in a day) events (Pattanaik and Rajeevan 2010). Most prominent extremes are caused by synoptic scale weather systems, mainly the low-pressure systems, leading to floods and landslide. The low-pressure system may intensify to depression or occasionally to a cyclone surrounded by convective clouds mass and give heavy rains. The rainfall activities in south west sector of the LPS (Godbole 1977; Sikka 1977). These systems remain active for 3–5 days and cover area more than 1000 km^2 . A cyclonic system of the intensity characterized for low has associated wind speed not more than 8.5 ms^{-1} and next stage of intensity, i.e. depression wind speed, ranges from 8.5 to 16.5 ms^{-1} . The low-level meridional wind shear linked with the ITCZ assists the processes involved in genesis of lows. Whole area of North Indian Ocean is known for formation of lows but comparatively more number of lows form in Bay of Bengal (BoB) because of high SST of oceanic water and the effective mixed layer not very deep and trough also passes through various sectors of BOB during monsoon season. The low-pressure systems generally follow monsoon trough (Goswami 1987) and their movement towards West and North West direction explained through change of Coriolis force across latitudes on movement track, i.e. beta-effect. Research studies (Dash et al. 2004; Pattanaik 2007; Prajeesh et al. 2013) are indicating decrease in frequency of depression from past few years although the total number of LPSs remained constant. The observed decrease in number of depression stage cyclonic systems in regions below 20°N latitude in the Bay of Bengal starting from 1950s is associated with declining trend of available moisture in the middle atmosphere, 600–300 hPa mainly over the Indian latitudes (Prajeesh et al. 2013). Pollution is also claimed as inhibitor of deep convective clouds and interaction among

clouds (Krishnamurti et al. 2013). Western Ghats experience 60% of extreme rain events synoptic disturbances (Francis and Gadgil 2006). Sometimes meso-scale convective systems getting moisture from local water bodies and thermodynamic support from heating may lead to local extreme rainfall. The increasing temperature in over Indian subcontinent enhance evaporation leading to more moist airmasses in the atmosphere which is a positive forcing for strong convection triggered extreme precipitation events (Kothawale et al. 2010).

The landslide increases in Nepal, India, Bangladesh, Bhutan and north Pakistan during the monsoon season. India and Nepal have high rainfall triggered landslide events which is about 21% of global rainfall triggered landslides mainly during monsoons (Froude and Petley 2018). There exists inter-annual variability in landslide incidences occurring in globe. The years with more landslide incidences found associated with regional well distributed rainfall patterns like positive rainfall anomaly but there is no simple relationship with ocean–atmosphere coupling like ENSO. The improved seasonal rainfall forecast which can capture temporal and spatial variation in active and break spells may be helpful for probable landslide zone identification and impact reduction particularly for major affected areas such as India, China and Nepal. Climate change is casually linked with landslides (Gariano and Guzzetti 2016).

4.6 Regional Trends in Monsoon

Walker (1910, 1914) found no trend in monsoon rainfall during 1841–1908 periods over Indian region. Kumar et al. (1992) have done a study on spatial and intra-seasonal nature of climatic trends of rainfall. West coast, North Andhra Pradesh and North West India are the areas where monsoon season rainfall trends were increasing, whereas in East MP and adjoining areas, North East India and some parts of Gujrat, the trends were decreasing. August rainfall contribution is more prominent to monsoon seasonal rainfall mainly over coastal areas of West and central parts of India. Parthasarathy and Dhar (1976) observed increasing trend for annual rainfall over East MP and West MP for 1901–1960 periods. Naidu et al. (1999) studied annual rainfall trends for 1871–1994 period; the negative trends are recognized in geographic region of west central India, middle parts of north India and north-eastern region of India. The enhancing trend observed over north-west India spanning states like Haryana, Punjab, Rajasthan and West MP, an isolated area in the east and the peninsular region.

Guhathakurta and Rajeevan (2008) observed no significant trend for monsoon and monsoon months for the country as a whole with large variations in different regions. The July rainfall is decreasing for most parts of the central and peninsular India but increasing significantly in the north-eastern parts of the country. August months' monthly rainfall has increased significantly (at 95% significance level) for the subdivisions Konkan and Goa, Marathwada, Madhya Maharashtra subdivision. Kerala and Tamil Nadu, dry days is on increase resulting in reducing trends of mean yearly rainfall. Rajeevan et al. (2008) examined variations in long period climatic

trends of extreme precipitation events over the middle India using 104 years (1901–2004) high resolution daily gridded rainfall data and found that SST fluctuations over Tropical Indian Ocean are linked with year-to-year and decade-to-decade variations of rainfall extremes. The strong connection between the SST over equatorial Indian Ocean and very heavy rainfall (VHR) events over the central meteorological subdivisions of Indian region will lead to more and more VHR events and further supported by the atmospheric global warming condition the floods occurrence will increase over central India.

Annual normal rainy days are nearly 10 over extreme west Rajasthan to 130 days over north eastern states of the country. The north eastern areas of the country, sub-Himalayan West Bengal and extreme western coast region receive approximately 100 rainy days in a year. The frequency of rainy days and heavy rainfall days are decreasing significantly over central, north and some areas of eastern parts of India. Wet days frequency is increasing over peninsular India, mainly Karnataka, Andhra Pradesh and some parts of eastern India. Positive trends in the frequency of heavy rainfall days are observed in parts of Konkan and Goa and adjoining coast and some areas of eastern India. Single-day extreme rain events are on rising over costal districts of Andhra Pradesh Orissa, West Bengal, some northeast regions and on west coast of India parts of Saurashtra and Kutch and east Rajasthan. The extreme induced flood situation and associated risk has increased manifold during past decades mainly over coastal states (Guhathakurta et al. 2011). Extreme rainfall frequency is on decreasing line over some areas of states like Chattisgarh, Jharkhand and some areas of north India.

Goswami et al. (2006) using daily realized rainfall data set found that amount and occurrence of extreme precipitation events are significantly rising and moderate amount events and their frequency are decreasing significantly over central India in monsoon season based on data from 1951 to 2000. Kumar et al. (2010) observed no significant trend to address the variations for yearly and monthly rainfall for India as a whole.

Singh and Mal (2014) studied rainfall trends and variability over western Himalaya and found declining trend in annual and monsoon rainfall over high altitudes and increasing over low altitude. Agarwal (1952) investigated the rainfall variations over middle geographic land areas of India and found a steady change which was not significant during 1908–1940. Temperature and precipitation data of Ganga Basin analysed by Kothiyari et al. (1997) shows that rainy days are decreasing, resulting in decrease of total monsoonal rain, and the annual record of daily maximum temperature is showing rise. These variations became noticeable after the year 1965, highlighting climate change signatures on regional scale.

Mullicka et al. (2019) analysed the trend of mean annual rainfall and reported increasing trend of 5.675 mm/y for Bangladesh during 1966–2015 period. The 1 day and consecutive 3-day maximum rainfall trends are increasing in few places and decreasing at other places with no significant change.

4.7 ENSO, IOD and MJO Links with Monsoon

Rainfall during monsoon season and associated planetary and synoptic scale circulation are mainly controlled by global parameters like ENSO and IOD, which are indicative of quantification of ocean–atmosphere coupling in which sea surface temperature also plays influential role. Mooley and Parthasarathy (1983) investigated the relationships of indices of dryness and wetness over India with SOI and SST anomalies are expected to be useful in understanding implications of large-scale anomalies in performance of Indian summer monsoon. Rasmusson and Carpenter (1983) and Shukla (1987) studied the link between the inter-annual variability (IAV) in the Indian summer monsoon rainfall (ISMR) and the El Niño-Southern Oscillation (ENSO) phenomenon. Yadav (2009) used surface temperature, pressure mean sea level (MSLP), geopotential height in the troposphere and global flow patterns of wind to study rainfall variations occurring over years for 1949–2005 period and found the El Niño-Southern Oscillation (ENSO) linkage with strength of monsoon has been deteriorated whereas it has become strong with SST over northwest (NW) of North Atlantic. Yadav (2008) established link between 2mST over tropical southwest Pacific and intensification of subtropical westerly jet over Indian Ocean and enhancement of monsoon circulation during negative phase of ENSO. While during non-ENSO year positive relationship of ISMR with 2mST anomaly over northwest of North Atlantic Ocean. Srivastava et al. (2020) observed ENSO impact on July and August rainfall and found significant changes at multi-decadal time scale. The influence of ENSO was significantly strong in August and significantly weak in July during 1948–1980 and post 1980s, ENSO monsoon relationship less strong in August than in July. During 2017 monsoon three regions Central India, West Central India and North East states experienced extreme events in active phase and northeast region of Himalayan range experienced during break phase. Most of the extreme events happened during July with significantly high seasonal frequency favoured by weak La Niña and positive Indian Ocean dipole (Suthinkumar et al. 2019). ENSO (El-Niño Southern Oscillation) term is used for ocean–atmosphere coupling. It is a combination of southern oscillation in pressure field and temperature oscillations Pacific Ocean. Warm Phase of ENSO means El Niño; above average SSTs over eastern Pacific and cool phase of ENSO means La Niña, SSTs in the eastern Pacific below average. ENSO have opposite phase relationship or the inverse relationship with Indian monsoon, i.e. warmer ENSO event weaker is the monsoon. Indian monsoon rainfall has strong correlation with anomalies of SST over Niño 3.4 region mainly. The negative SST anomalies over crossing threshold (-0.5 °C) lead to La Niña event and above-normal or excess rainfall over the country. The La Niña events have positive influence on monsoon and its seasonal variation. The positive SST anomalies corresponding to El Niño over Niño regions [Niño1 + 2 (0° – 10° S, 90° W– 80° W), Niño 3 (5° N– 5° S, 150° W– 90° W), Niño-3.4 (5° N– 5° S, 170° W– 120° W), Niño-4 (150° W– 160° E and 5° N– 5° S)] lead to deficient or below-normal rainfall and weak monsoon over the country. This SST–Monsoon correlation is also changing with decadal–epochal oscillations. The seasonal rainfall time-series have epochs of more than and less than the mean

rainfall. El Niño with below-normal rainfall Epochs will be more severe creating rainfall deficiency and similarly La Niña with above-normal rainfall Epochs will give surplus excess rains. The major rain related extremes events (massive flooding/acute droughts) are because of the reason that external forcing, i.e. El Niño and La Niña, variability and epochal variability are in same (Krishna et al. 1999).

The ENSO-monsoon relationship seems weakening (Kumar et al. 2010) in recent decades due to shifting of walker circulation anomalies south-eastward causing reduction in sinking motion over Indian region and favouring the monsoon. The persistent higher surface temperatures in winter and spring over Eurasia, the mid latitude warming enhancing land ocean temperature contrast required for monsoon.

The effect of ENSO on monsoon rainfall and its intra-seasonal variations are also influenced by Indian Ocean Dipole (IOD). The oscillations in SSTs over the eastern and western sides of Indian Ocean form the dipole. The dipole moment index (DMI) is used to quantify the Indian Ocean warming influence on monsoon rainfall. Positive IOD is favourable for monsoon rainfall and negative IOD is unfavourable for the monsoon. During the period 1958–1997 the El Niño/Southern Oscillation (ENSO) and IOD behaved in complementary manner with each other and overall balancing of monsoon rainfall during the last four decades claimed by research studies (Ashok et al. 2001). The temperature dipole in Indian Ocean (IOD) is acting as a modulator of rainfall over the Indian subcontinent and redefining the correlation between monsoon rainfall and ENSO.

Another important factor causing intra-seasonal variations in monsoon rainfall is Madden Julian Oscillation (MJO). Pai et al. (2009) analysed the linkage of various phases of MJO on day-to-day variation of monsoon rainfall. As MJO moves eastwards, northward shift of rainfall belt from peninsular India takes place. The above-normal rainfall band is observed along monsoon trough region in 5 and 6 phases of MJO. When MJO moves in 7, 8 phases, there is decrease in rainfall over various parts of country. MJO phase 1 and 2 are unfavourable for monsoon rainfall activity. MJO plays crucial role for onset of active rainfall spells and break spells and their duration. The amplitude of MJO is significant in this connection but phase of MJO is more important as related to a region.

4.8 Climate Change and Global Warming Impacts

Warming temperature trends, high magnitude extremes, are prominent over the interior land masses of various parts of Asia. From 1900 to 2005, precipitation declined in parts of southern Asia (IPCC 2007). The global warming will be enhancing and climate models are forecasting increase in annual and monsoon rainfall over Indian region. There is high probability of precipitation extremes to increase during monsoon season over various parts of southeast sector of Asian continent. All available climate-related models with the maximum possible emission regimes all are projecting rise of mean and extreme precipitation in Southern Asia (SAS). The different phases of Coupled Model Inter-comparison Project, mainly phase 3 (CMIP3) and Phase 5 (CMIP5), are forecasting weakening of large-scale monsoon circulation in future (Kripalani et al. 2007; Sooraj et al. 2015; Krishnan

et al. 2012). The changes in location, intensity of large-scale systems like monsoon trough over Indian region, the Mascarene High, the western North Pacific (NP) subtropical high, and the upper tropospheric South Asian high are projected (Preethi et al. 2017). There is no clear consensus in models about genesis and track modification in future warming scenarios but more extreme rainfall events are projected over the coastal areas where cyclone landfall is expected to occur. The recent Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations with Representative Concentration Pathway (RCP) framework are forecasting positive dilation of mean temperature greater than 2 degrees change in mean annual temperature above the reference temperature of late twentieth century over the most of the countries across the globe in the middle of twenty-first century according to RCP8.5 and are above 3 °C for countries situated in Southeast sector of Asia having high population density and big coastal boundary and of the order of 6 °C or even more over higher latitudes in the second half of twenty-first century. Model projections have uncertainties posing challenging situation for policy makers. Looking for more reliable forecast for South Asian monsoon (SAM) the uncertainty/over projection should be identified scientifically. The internal variability is mixed with forced rainfall trends, leading to over-projection, and inter-decadal Pacific Oscillation (IPO) is identified as cause of more uncertainties (Huang et al. 2020). The improved IPO predictions can considerably remove near-term over-projections of SAM.

Worldwide mean temperatures will be on rising trend during span of twenty-first century if greenhouse gas (GHG) emission remains on similar pattern of increase. The global temperatures averaged over the period 2081–2100 are projected to likely exceed 1.5 °C above 1850–1900 average temperature threshold. Heavy rainfall frequency will increase over many parts of South Asia. Increased count of warm days and less count of cold days are likely to remain on same track as the warming is likely to enhance in future century also. The problem of water scarcity will be amplified by increasing population and high sub-regional variability of precipitation. The well-known most fertile plains of Ganga may have 50% decrease of crop yield wheat due to expected double CO₂ emissions. Rise in sea level will inundate lower areas and Mangroves, salt marshes, and sea grass beds and rice growing regions may decline. Over Indian region localized heavy to very heavy rainfall events reported an increase during past 50 years. Land use pattern and urbanization and geographic location are the factors enforcing localized events. The year-to-year variations of monsoon will be more pronounced during twenty-first century. Heavy rainfall events and localized intense rainfall events will be enhancing flood risk as per Ministry of Earth Science (MoES) report 2020. The westerly wind over north Arabian sea brings strong moisture carrying spells and gives rise to exceptionally heavy rainfall events over districts of Gujarat and landlocked areas of Central Indian region. The main reason behind it is warming of north Arabian sea due to carbon emission making winds more variable. In ongoing climate change and warming scenario, pole ward shift of low-level jet is projected leading to more dry days and variation in precipitation over west coast adversely affecting biodiversity of Western Ghats (Sandeep and Ajayamohan 2015).

Floods are the result of monsoon extremes causing loss of human and animal life and property. Major flood events with largest loss of human lives and property

occurred over the central India in 1989 and 2000, Mumbai in 2005, Uttarakhand floods 2013, Kerala floods 2018, etc., which resulted from 3 to 4 days continuous raining supported by westerly flow from the Arabian Sea. In 2016, due to heavy rainfall, widespread flooding damaged life and properties over west coast, Mumbai. The Kaziranga National Park in Assam submerged due to extreme rain. Drought is another climate extreme that arises due to rainfall deficiency. Although monsoon total rain remains normal, certain districts remain deficient in rainfall and suffer from drought. Drought is not instant but cumulative deficiency of rainfall for months and years. Drought declaration and management is state subject in India. Almost every year each state has some districts under drought conditions in spite of normal rainfall because of high spatial variability in rainfall. In 2016, 46 districts were drought affected in M.P. and in 2019 again 36 suffered acute drought conditions. In 2018, 18 districts of Jharkhand, in 2019, due to weak northeast monsoon, 23 districts of Karnataka suffered drought. Similarly, other parts of the country are also facing drought conditions mainly before and after the onset of monsoon and sometimes even in monsoon months. Delay of monsoon rain intensifies use of ground water resources, high heat leading to fast evaporation of water from surface water bodies and drying them fast and creating water scarcity in drought-affected area. Drought becomes more severe if it occurs during consecutive years at the same place. IMD can declare drought when rainfall is deficient or less by 10% and spatially 20–40% geographic area of the entire India is encountering dry weather situation or no rain type of situation. Rainfall-related drought is termed as meteorological drought but agricultural drought is different from it and several other crop-related parameters are taken into account for agricultural drought. Mainly lack of rainfall or uneven rainfall can lead to agricultural drought-like situation. In Rajasthan in 2002, due to almost 50% less rainfall as compared to July month normal rainfall, farmers could not sow kharif crop and drought was declared. The concept and definition of drought is subjective in nature. The methodologies for assessment and parameters under consideration are changing from state to state. In order to address various issues associated drought declaration and bring some uniformity in the process government of India brought the new guidelines for drought declaration in 2016. The monitoring of drought is done by Crop Weather Watch Group (CWWG) central and state level having responsibility of regular interactions, analysis of data coming from various institutes and government bodies and assessing its impacts on crop. The new guidelines brought by Indian government drought declaration given first priority to Meteorological information (a) the rainfall measured by the percentage deviation in rainfall from average or the Standardized Precipitation Index (SPI) along with the information of dry spell. Looking for future changes in critical meteorological parameter, standardized precipitation index (SPI) new research study (Guhathakurta et al. 2017) projected that out of 32 meteorological subdivisions seven are serious track of spatial increase of drought hit districts mainly covering states like Uttar Pradesh Uttarakhand, Jharkhand, Chhattisgarh, Kerala and seven sister states of India. Although many areas of India located on eastern side and northeast region have increasing percentage of areas hit by water shortage condition and drought, but still the SPI-based trends are not significant (SPI values with moderate dry, severely

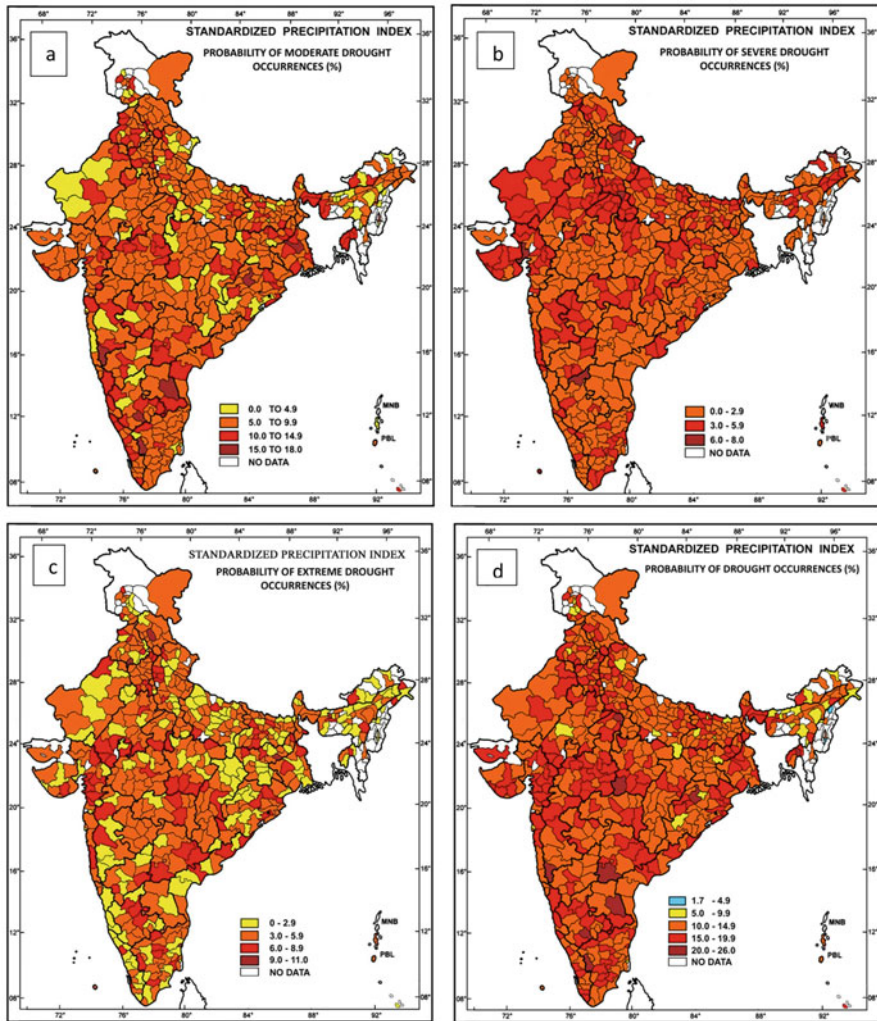


Fig. 4.4 Probability of occurrences of (a) moderate drought, (b) severe drought, (c) extreme drought, (d) combination of all drought types: Reproduced from Guhathakurta, P., Menon, P., Inkane, P., Krishnan, U. and Sable, S., 2017. Trends and variability of meteorological drought over the districts of India using standardized precipitation index. *Journal of Earth System Science*, 126(8)

dry or extremely severe dry conditions). Significantly decreasing trends are nowhere observed in Indian region. The probability stating that drought will occur in every district under three main categories of drought, i.e. moderate, severe or extremely severe and sum of all, over India using 1901–2015 data are shown in Fig. 4.4. Almost all states have some districts vulnerable to extreme drought conditions.

The evidence of observed climate change data during twentieth century highlighted the food grain availability issue and region-specific climate modifications have shown their signatures to noticeable extent to the scientific community. Nowadays, various models duplicating the various crop processes known as simulation models are being used to understand the influence of climate change on production and management practices of crops. The output generated by simulation models with some value addition can be shared with farmers, which can guide them to opt better management skill and technology and suggest them appropriate alternatives for their farming, thus making agriculture economically stable. In India, substantial research and analysis work has been done focusing on building an understanding of nature and amount of change in yield of various crops under the conditions of forecasted climate change (Aggarwal 2003; Uprety and Saxena 2021). The repeated droughts and massive floods seriously imperiled the working and earning conditions of billions of people depending on land and other natural resources for most of their needs (Hamdani Rizwana and Pathan 2016). The failure of monsoon increases pressure on available forest resources like trees, grasslands and water ponds and over-exploitation accelerates drought during dry years, hitting hard to soil moisture content and increasing dryness in soil making it loose and vulnerable for erosion.

The agricultural response to climate change will be the major deciding factor about the future food security in South Asia. Agricultural sector is very much sensitive for climate variations but it is one of the critical drivers for climate change. The modification of agricultural management practices according to weather changes and yield optimization are challenges for agricultural sector. The regional variation of weather parameters like temperature, rainfall, evapotranspiration, sun shine hours, crops and cropping patterns brings uncertainty in agricultural response to climate change. The crop damage/losses may be increasing if the forecasted climate change crosses the climate variability limit.

Scientific analysis and research done by Indian Agricultural Research Institute (IARI) and various other institutions estimated more loss/damage for Rabi season crops. Corresponding to each 1 °C increase in temperature, wheat production gets reduced about 4–5 million tonnes. Even small variations in temperature and precipitation have considerable impact on the quality and quantity of various fruits, green vegetables, tea, coffee, aromatic plants and medicinal plants and basmati rice. The population of pathogens and insects have direct link with temperature and humidity of air. The alterations in weather condition play a dominant role in regulation of insects and pathogen population. The other diverse impacts of climate change on allied agricultural sectors include low productivity from dairy cattle and slow rate of fish breeding, migration of agri-employed population and poor harvests. Agricultural efficiency/output is reactive to two main types of broad climate-associated effects: primary effects by variation of temperature, rainfall and carbon dioxide concentrations and secondary effects from soil moisture and diverse spread and occurrence of pest attack and linked diseases. The productivity of main food crops rise and wheat estimated to decrease by considerable quantity with forecasted climate changes (IPCC 2007).

The climate change affects physiological response of the plant enhancing vulnerability of agricultural production system. The estimated net revenue loss at the farm level is around 9% to 25% for 2–3.5 °C increase in temperature. Scientific community also calculated that a 2 °C increase in average temperature and a 7% enhancement in average rain would decrease total revenues by 12.3% for entire India. Agricultural activities and production in coastal land areas of Gujarat, Maharashtra, and Karnataka states are bearing most adverse impacts of climate change. Agricultural losses of various extent come to notice from the major food-grain producing parts of states like Punjab, Haryana, and western Uttar Pradesh. On another front, states like West Bengal, Orissa, and Andhra Pradesh are forecasted to gain advantage to little extent due to warming (Aggarwal et al. 2004).

The period of unusual dryness is a normal feature of the climate and weather system in semi-arid and arid regions of the tropics, which covers more than one third of the land surface and is vulnerable to drought and desertification (Nagarajan 2003). Drought is seen as an outcome of monsoon failure causing to be occurring due to monsoon failure causing crop under stress, demand for supportive management practices. Intense drought leads to complete crop damage, fast drying of natural ecosystems and lack of drinking water leading to undue hard work for the rural and urban communities (NDMD Moha. GOI 2000).

Maharashtra state has some drought-affected districts almost every year but some districts received even less than half of normal rain during two consecutive years, almost 15,000 villages and 15 districts declared drought affected. So continuous poor monsoon for 2 years caused the question of livelihood for the rural and semi-urban population. Monsoon failure generates need of immediate help for villagers for their survival (Hamdani Rizwana and Pathan 2016; Warde 2016).

4.8.1 Remedial Measures

1. Effective monitoring and regulation of available sources of water in areas encountering problem of drinking water.
2. Arrangement of green fodder for cattle and other animals in drought-affected villages and districts.
3. Provide alternative means for livelihood and assured supply of eatable items and food grains to people through effective management of public distribution system (PDS).
4. Farmer awareness for adoption of drought-resistant varieties of crops and weather-linked new cropping practices and technologies.

4.8.2 Impact of South Asia Monsoon on Society

The high variability of South Asian monsoon and climate change are hitting hard densely populated South Asian region. The impacts of climate extremes are closely tied to population distribution, regional geography and development activities.

Monsoon in Indian subcontinent demonstrate large-scale atmospheric processes and important component of global climate system. Flood, drought, landslide and thunderstorms are the associated extremes affecting the population. Floods are natural disaster that account for 50% of the mortalities occurring because of extreme weather events (EWEs; Ray et al. 2021). Flood-associated mortalities reduced about 3–5% per decade since 1980 to 2009 and 20% reduction is seen in the recent decade, even with rise in flood frequency in India. The average frequency of cyclones per year has increased a little (2.0) in comparison to years of previous decades (1.7). The associated mortality rates have declined by 94% during last two decades (Ray et al. 2021) mainly due to improved model forecast, accurate track prediction and good management by Government of India (GoI). Loss of human life, livestock, crops and property, damage to kutcha houses, roads, and railway tracks, breaking of bridges and dams, inundation of low lying areas, disruption of electric lines and local connecting routes, overflow of rivers and deterioration of water quality due to mixing of water coming from various sources are the immediate impacts of flood event. Rural employment, food security, migration of population for livelihood and health issues like waterborne diseases and with time lag vector-borne diseases spread or outbreak in affected population. Some well-known waterborne diseases are typhoid fever, cholera, leptospirosis and hepatitis A and vector-borne diseases are malaria, dengue and dengue haemorrhagic fever, yellow fever, West Nile Fever, etc. These are commonly observed during and after flood situation. Flood are known for associated diarrhoeal diseases causing significant morbidity and mortality in flood prone areas of the world. According to World Health Organization (WHO), flood of 1988 in Bangladesh, diarrhoeal disease accounted for 35% of all types of illnesses associated to floods and 27% of 154 deaths associated to flood out of total 45,000 patients in rural areas of Bangladesh. Large number of cholera cases were reported during 1998 floods in West Bengal. The coastal populations in South Asia are becoming more vulnerable for cholera outbreaks with increased SST and algal blooms (Huq and Reid 2007). Thunderstorms and lightning events are common in monsoon season and severe thunderstorm/lightning associated strong wind damage crops, trees and structures and even claim life of people. Lightning events and associated mortality rates are showing significantly increasing trend over the past four decades (Ray et al. 2021). The farmer community mostly hit hard by flood and excess rain. Excess rain damages the crop and reduces productivity. The problem of soil erosion is quite common. Specially in coastal areas where cyclone brings salty water to land during flood situation creates problem of soil fertility. The cities have grown with fast pace during past decades and generated problem of urban floods. The urban floods are more impactful as the urban areas are the main controller of economy. Most of the urban floods are not due to weather but due to human unplanned development, rapid urbanization and lack of proper drainage system and also effective application of technological tools during disaster management process.

Drought is climatic extreme which is subjective in nature and shows its signature almost every year in various regions of Indian subcontinent. Drought causes crop failure, depletion of surface water resources, more exploitation of ground water and

creates food scarcity for the population leading to migration of population from one place to another in search of livelihood. Climatic extremes like flood and drought threaten food security, food items become inaccessible for some fraction of population and social fragmentation becomes more evident in population. Looking at the past eighteenth century which was famous for long droughts witnessed great political turmoil across Southeast Asia, during extended periods of drought of the past centuries. Coming to recent decades, water availability and crop-linked four kinds of droughts, i.e. meteorological, hydrological, soil moisture also known as soil water and greenery or vegetation drought, have high seasonal and spatial variation. The hydrological and greenery/vegetation droughts cause more impact on growth, quality and quantity of crop than meteorological and soil moisture droughts (Xiang et al. 2017).

Extreme climatic events as visually generate many adversities in social life and act as natural cleaning agents of natural and social atmosphere. During extremes various faults in management and technological practices and social gaps become more evident and thus opens the path for the science and society to identify the need and accordingly guiding the scientific community too.

4.9 Summary

The chapter deals with various kinds of monsoonal extremes such as floods and droughts resulting from accumulative variation in monsoon season and landslides and flash floods like weather extremes caused by lows and depressions and climate change aspects over South Asia. Along with extremes large-scale circulation features of monsoon, i.e. semi-permanent synoptic systems and probable implication of climate change, have been discussed.

The ocean–atmosphere coupling indicator like ENSO and El Niño, La Niña conditions have been linked with floods and droughts in Indian subcontinent but all the droughts are not due to El Niño and all the flood extremes are due to La Niña. The connection of ENSO with inter-annual variability (IAV) of the Indian monsoon rainfall has weakened while relationship with the northwest (NW) of North Atlantic sea surface temperature (SST) has become strong during recent decades. The ENSO monsoon relationship is changing due to shifting of Walker circulation anomalies south-eastward and mid latitude warming. Also the IOD behaved complementary to ENSO during past few decades. The seasonal rainfall time series epochs of below-normal/above-normal rainfall coincide El Niño/La Niña resulted in major climatic extremes like flood and drought. Overall seasonal extremes are governed by external factors like ENSO, IOD, NIO, etc. and through natural dynamics. Monsoon intra-seasonal oscillations (MISO) are observed through low-pressure systems (LPSs) forming in Indian Ocean region and moving North, North Northwest, North Westwards give extreme rainfall over large geographic area covering many cities. More LPSs form in Bay of Bengal (BOB) than Arabian Sea. Recent years depressions are less as compared to lows. Why lows are not intensifying to depression or less depressions in monsoon season is still not clear. Reduction of relative humidity

between 600 hPa and 300 hPa levels of atmosphere over the Indian latitudes and pollution claimed for less depressions during monsoon.

The precipitation extremes linked with monsoon are very likely to increase over East, South, and Southeast Asia. All climate models project are projecting an increase in both the mean and extreme precipitation in Southern Asia (SAS) during late twenty-second century.

The frequency and probability of extreme rainfall events increased over South Asian regions and likely to be on same track under climate change impacts but contrasting trends also observed in various regions on India, Bangladesh and Pakistan.

The significant increasing trend of frequency of rainfall extremes (rain above 124.4 mm during 24 h) mainly at districts of west coast and some land areas of central and northeast region of India. The increased number of rainfall extremes is compensated by a considerable decrease in number of moderate and heavy precipitation events (≤ 64 mm in a day) and balancing overall monsoon robustness. There is no statistically significant trends for annual, seasonal, and monthly rainfall over Indian region whereas mean annual rainfall increasing trend of 5.675 mm/y. for Bangladesh during (1966–2015). The frequency of rainy days is decreasing significantly over central, north and some areas of eastern parts of India and wet days frequency is increasing over peninsular India. Single-day extreme rain events has increased over coastal states and parts of northeast India and some parts of Bangladesh. The core monsoon region, i.e. central India, extreme associated to heavy rain events are influenced by variations of SST over Indian Ocean and number of extreme rainfall events estimated to rise in coming future under warming and associated floods will also increase. Floods are frequent in South Asia. Nepal, Bangladesh and Indian states encounter flood during monsoon. The flood water carries silt load and deposits in plains; the course of river also changes sometimes, like river Kosi in Bihar. Floods submerge hectares of farmland and destroy crops, loss of life, livestock and property and cause landslides in hilly regions. India and Nepal have 21% of global rainfall triggered landslides mainly during monsoons. The problem of safe shelter to the people and water quality arises concerns mainly during floods. Bangladesh is one of the world's most densely populated countries and prone to cyclones and flooding due to its low-lying position, so it is more climate-sensitive economy. Major floods are quite often in phase with active spell and drought is accumulative picture of dry days. The drought is subjective in nature and methodologies for assessment and parameters under consideration vary from region to region. The number of dry days, dry spell information, Standardized Precipitation Index (SPI) values along with rainfall departure from normal have been included in the list of important parameters for drought declaration in India. Area under drought-affected districts is showing significant increasing trends or no trend in India. Drought situations occur every year in many states of India and some coastal states like Tamil Nadu, Kerala and Karnataka. Flood and drought both lead to question of food security and health issues due to diseases outbreak linked with post flood weather conditions.

Coming to climate change and warming aspects, South Asian regions observed decline in precipitation from 1900 to 2005. The monsoon extremes very likely to increase over East, South, and Southeast Asia. The recent Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations with Representative Concentration Pathway (RCP) scenarios are projecting greater than 2 degree rise in average mean yearly temperature with respect to reference level temperature of period 1970–1999 twentieth century estimated by ensemble of climate over huge and extensive land mass of the world during middle of twenty-first century under RCP8.5, and above 3 °C over continental land areas of Southeast sector of Asia in the late twenty-first century. Increased frequency of heavy rainfall with non-uniform spatial and temporal distribution, more number of warm days, and less cold days will be increasing and create acute water scarcity problem amplified by rising population and its demands, huge pressure on natural resources and ecosystems, extinction of more species, and loss of biodiversity.

The large-scale circulations associated with SAM will be modulating under the warming atmosphere. Weakening of circulations projected by models but extremes will increase. The future modulation of six semi-permanent synoptic circulation will lead to more extreme events. The future poleward shift of LLJ. The position of Tibetan anticyclone and associated wind strength determining reversal of temperature gradient in troposphere will be playing crucial role for monsoon advancement in South Asia. Large-scale circulations inducing/favouring regional circulation modifying regional weather and governing internal variability of monsoon will be more pronounced under changing climate. The projections of climate models with probable emission ranges have deviations and uncertainties. The reduction in range of uncertainty is required for planning technology driven solutions and sustainable practices for better adaptability of changing climate.

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